MINISTERUL EDUCAȚIEI ŞI CERCETĂRII

ROMÂNIA

UNIVERSITATEA DE ARTE "GEORGE ENESCU", IAŞI

TEZĂ DE DOCTORAT

Rezumat - Summary

Sistemele acustice muzicale – trecut şi prezent

Conducător ştiințific

Prof. Univ. Dr. Gheorghe Firca

Doctorand

Ion-Cristian Nițu

2007

FOREWORD

From immemorial times, people were interested in the music art and also in the science of sounds. Even from the early antiquity the music was studied by scholars from all over the world: chinese, indians, greeks or arabs. They noticed that the musical phenomenon cannot be defined only in its own universe, being essential to be observed from a wide examination and defined on physical and mathematical basis. In addition to the musical disciplines – composition, aesthetics, and performing – were promoted another ones for defining particular aspects of the music science. The most important discipline is the music theory dealing with specific phenomena, from the graphical notation to the music scales. Another music discipline, the organology, provided the theoretical and practical basis of music instruments construction. The theorists from all times tried to establish very rigorously the music rules in connection with the universe laws. In *Traité de musicologie comparée* Alain Daniélou said: "the numerical relations expressing the musical sound ratios have synonyms in all the other aspects of reality [...] Thus we conclude that the laws ruling the world of sounds are not belonging only to this domain, being in fact in close relation with the universe rhythm".

The contemporary interest for ancient music causes a growing research in the old musical scales and also the seeking of simple methods for manufacturing of musical instruments able to be tuned in many musical scales.

We can notice that natural sounds on the one hand and their reception by biological receivers on the other hand are defined in different ways based on specific phenomena. Sound production is based on specific vibration modes in strings and tubes, generating harmonic oscilations (the phenomena can be defined with simple mathematical relations). Reception depends on hearing characteristics, having a linear variation of sensation (physiological unit) for a logarithmic variation of the sound frequency (physical unit).

In the musical domain we cannot consider only the generation or reception of the sound, because the two phenomena are interrelated; even so, the generation – reception pair is making a lot of impediments in the theoretical and practical analysis. Due to the dissimilar laws ruling the sound generation and reception, considering both phenomena in the music theory and organology led to different approaches. Some used the numerical form (by mathematical ratios) according to the sound generation, based on division or harmonics (Pythagorean and just intonation); others represented the laws of sound generation by the means of physiological terms (temperaments); the results were not satisfactory.

For explaining as exactly as possible the musical scales we must present the physical phenomena, the methods and appliances for sound measuring and computing and also the evolution of musical instruments.

1. PHYSICAL ACOUSTICS

The chapter ***1. Physical acoustics*** presents the basic elements of physics dealing with vibrations: generating and transmitting. This domain must be reduced to musical related aspects, studying only the vibrations perceived as sounds. In this chapter are presented also the waves and sound characteristics.

1.1. Waves show informations about oscillations, equations, Huygens' law, diffraction, reflexion, refraction, interference, Doppler-Fizeau effect, Fourier analysis, reaction, resonance.

1.2. Sound properties presents a definition and a classification based on frequency, intensity, spectrum, duration and transients.

1.3. Sound production deals with generators, as following: acoustical generators (tubes, strings, bars, membranes and plates), mechanical generators (tuning forks, sirens, flutes, air generators), electromechanical generators (speakers, crystal and magnetic generators), thermic generators and the human voice as the most interesting generator.

1.4. Sound radiation presents the wave definition defining also the speed, wavelength, acoustical field, intensity, difraction and absorbtion.

2. TECHNICAL ACOUSTICS

The chapter ***2. Technical acoustics*** deals in the first part with the electronic systems used for generating, capturing, reproduction and also for recording the sounds. In the second part are shown the devices used in acoustic laboratories. The third part deals with room acoustics.

2.1. Sound generation presents the electronic circuits used for generating sounds. The circuits are named electronic generators.

2.2. Sound capturing and reproduction shows first the process used for transposing the entire sound scene into electric signals (by using microphones) and secondly the devices used for reproducing the sounds (speakers).

2.3. Sound recording reveals the devices used for magnetical and optical sound recording.

2.4. Apparatus for sound studies presents the devices used in the sound laboratories: generators, filters, oscilloscopes, digital frequency counters and the melograph.

2.5. Rooom acoustics deals with the specific elements for designing the rooms used in musical activities. In this domain is essential to consider geometrical aspects (shape and dimensions) and physical aspects (reverberation time, clarity and diffusion).

3. THE ACOUSTICS OF MUSICAL INSTRUMENTS

The chapter ***3. Musical instruments*** focuses on organology considered as objects for generating musical sounds for accompanying drama, ceremonies, rituals, games and other human activities. It is difficult to make a classification of the musical instruments because of the great variety of tipes of construction and specific ways of working. In the ancient Greece were only two kind of instruments: string instruments and wind instruments; the ancient Chinese based their classification on material, having instruments made of hide, stone, metal, clay, silk, wood, bamboo, gourd. The Indian theorists arranged the musical instruments as string instruments, wind instruments, percussion instruments (idiophones or excited through the agency of tightly stretched membranes). Since 1914 it is used the system proposed by Erich Moritz von Hornbostel and Curt Sachs, keeping the distinction made by Victor-Charles Mahillon concerning the vibrating element and the particular way this one vibrates. Considering the way the sound is produced, we have idiophonic instruments (***3.1.***), instruments using tightly stretched membranes (***3.2.***), wind instruments (***3.3.***), string instruments (***3.4.***) and electric instruments (***3.5.***). A special category gathers the musical automates (***3.6.***). Musical instruments may be classified by taking into consideration the energy for vibration, the possibility of variating the sound, the number of simultaneos sounds.

4. PHYSIOLOGICAL ACOUSTICS

The chapter ***4. Physiological acoustics*** presents the process of sound generation by the human voice, the hearing process and the physiological characteristics of the sound.

4.1. Sound generation – the human voice enumerates first the theories about the way the human voice is generating the sound and secondly presents the structure of the human voice.

4.2. The audition process presents in detail the anatomy of the hearing organ (internal structure).

4.3. Physiological characteristics of sound shows the way in which sound is perceived as hearing sensations, showing also the correlation between the physiological and physical properties of sound: pitch – frequency, loudness – intensity and timbre – spectrum. Very important is the correlation of the variation of these pairs of elements and also the sensibility.

5. MUSICAL ACOUSTICS

Musical acoustics studies the sound phenomena considered in correlation with the art of music: sound generation in musical instruments, musical structures, intervals, scales and modes. The chapter ***5. Musical acoustics*** presents the evolution in this domain, the musical treaties, the harmonics, intervals and scales.

5.1. The evolution of musical acoustics presents a review of the musical acoustic as a science. For a long time the musical intervals were defined by mathematical ratios of the monochord. In time this approach became inappropriate for the theorists, which were considering the ratios too abstract, looking to define the sound by studying the physics of sound. In the 17^{th} century were made the first steps for founding the music acoustics and in the next two centuries the researchers were interested to determine the frequencies of the vibrating objects. The 20^{th} century was the time of experiments when the researchers having at hand a lot of electronic apparatus and computers were able to push forward the knowledge in musical acoustics.

5.2. Musical theory treaties traces the developing of the theoretical thinking, through the agency of treaties, from the mathematical view of the music theory (the Pythagorean school), continuing with the physical approach (Marin Mersenne, Jean-Philippe Rameau, Joseph Sauveur), the pair of sensorial perception – abstract thinking (Francisco de Salinas), the theoretical thinking (Boethius and Gaffurius), the practical approach (Guido d'Arezzo) to the 20^{th} century approach (Arnold Schönberg, Paul Hindemith, Iannis Xenakis, Milton Babbitt and Allen Forte).

Music theory is the branch of the music study offering a scientific base for the study of the constituent elements generated by the duration and pitch of sound. It deals with notation, intervals, scales but it can also refer to melody, rhythm, counterpoint, harmony, orchestration and composition in a broader view.

The term *theory* comes from ancient greek meaning studying or observing. From ancient to modern times music theory passed through more stages from the mathematical to the physical view, from abstract to practical, reaching lastly even the encyclopaedic thinking.

5.3. Natural harmonics are regarded as sets of musical notes whose frequencies are related by simple whole number ratios. The subject was studied by

Gioseffo Zarlino, Marin Mersenne, Joseph Sauveur, Jean-Philippe Rameau, Giuseppe Tartini, Hermann von Helmholtz and Jean Baptiste Joseph Fourier.

5.4. The monochord focuses on the ancient single-string instrument, which was first mentioned in the ancient Greece, presumed to be an invention of Pythagoras. The theorists used to divide the monochord in two different ways: descendant (in the ancient Greece) and ascendant (like Boethius, Odo d'Arezzo, Johann Neidhardt and Friedrich Wilhelm Marpurg did).

5.5. Musical scales presents two classes of scales: those considered as just intonation (used by the human voice, wind and string instruments) and temperaments (used by fretted and keyboard instruments). The scales are presented in this order: ***5.5.A.*** Asiatic systems (Arabian, Indian, Chinese, Japanese, Korean, Vietnamese, Burmese, Thai, Javanese); ***5.5.B.*** Pythagorean and Zarlino's intonation; ***5.5.C.*** temperaments; ***5.5.D.*** just intonation; ***5.5.E.*** mean-tone temperaments (the eight tierces scale and the French, German and Italian scales); ***5.5.F.*** irregular temperaments; ***5.5.G.*** Marin Mersenne, Joseph Sauveur, Nicolaus Mercator and William Holder, Paul von Janko, Wesley Woolhouse temperaments and equal temperament; ***5.5.H.*** Byzantine scales presented by Chrysant (taken also by Macarie) and Anton Pann scales; ***5.5.I.*** microtonal scales; ***5.5.J.*** suitable systems for Johann Sebastian Bach's *Well-Tempered Clavier*; ***5.5.K.*** microintervals used in temperaments.

5.6. Methods for analysing the musical scales - the diversity of musical scales used in time made music theorists to try finding efficient methods for studying and comparing the given scales. The ideal solution proved to be an unique temperament containing in it's own structure the other musical scales.

5.6.1. Methods for merging the musical scales

The specific formulae for musical scales are very different, even incompatible, making impossible a comparative analysis for these scales. A simple method used in this analysis uses the direct comparison between the intervals in the named scales, obtaining a set of numerical values with many decimals. A more ellaborated method for analysis uses the transformation of the intervals for each scale by specific formulae. In this case we need to change the nonlinear mathematical functions into liniar relations, expressing the intervals by using logarithms because the sensations are determined by logarithmic relations. The best method in this case is to use the binary logarithms that determine also the hearing characteristic. A simplified variant of the last method is the construction of scales by having the steps being included in the terms of a geometrical progression. By unifying the scales, all the intervals used in different scales would be part of the terms defined by the *unique temperament*. This new temperament may be obtained by the use of some rules named *unification theorems*.

The first theorem of partial unification says that any temperaments might be reduced to a single formula by determining the least common multiple of the divisions for the given scales.

A variant of this method is that one in which we take one temperament as being the reference, transforming the others in accordance with this one. In this case we define *the second theorem of partial unification* which says that the temperaments might be reduced to a single scale by calculating them to the reference temperament.

The just intonations have a great variety of intervals apparently with no relation between them. In practice if we choose a very little measure we can find the division of a temperament to comply with the pure intervals. In this case we must define *the partial transmuting theorem* which says that any just intonation might be determined as a temperament by taking its interval steps from the terms of a geometrical progression. The ratio of this progression must be defined by the smallest interval used in the just intonation or as the difference between two intervals of this kind.

The next step to the general unification of scales is defining the *unique temperament* that will contain inside its own divisions all the intervals used by the musical scales, temperaments or just intonation. In this case we use *the general unification theorem* as follows: any scale (just intonation or temperament) might be reduced to a sole expression named the general temperament formula, defined as a geometric progression ($a_n = a_1 \cdot q^{n-1}$ or $a_n = 2^{n/m}$, where n is the index of the given step and m is the number of divisions of the unique scale. In addition to the last theorem we have two corollaries. The first says that the intervals of all the scales are among the values inside the general geometric progression. The second tell us that the progression's ratio may be obtained as the root of the least common multiple of the divisions for the given scales. The ratio must comply with the following condition: the differences between the new determined intervals and the given intervals must not exceed the frequency discrimination (about 3 Hz or 3 ‰ in the medium range – around 1.000 Hz). For more details on this subject we need to talk about some aspects of physiological acoustics.

5.6.2. Physiological acoustics **-** the researchers demonstrated that the musical pitch is proprotional with the natural logarithm of the ratio between a given frequency and the lower perceptible frequency. They observed that the ear is not able to feel the variation of a sound if that variation remains under a specific value. The minimal variation, called frequency discrimination, reaches 12 ‰ in the bass range, 3 ‰ in the medium range (500 – 3.000 Hz) and 7 ‰ in the treble range. Because the music theorists are interested only in the medium range we may use only the 3 ‰ value which is the maximum for the human musical frequency discrimination.

5.6.3. Historical review of the merging method – during time the theorists tried to define temperaments for reproducing as true as possible just intonation for obtaining more consonances. Some authors defined temperaments with very small divisions for describing all scales – just intonations or temperaments. These temperaments were made by Nicolaus Mercator (53 divisions), Wesley Woolhouse (730 divisions), Sir Jacob Herschel (301 divisions). Alexander John Ellis used 1200 divisions within the octave, named cents.

5.6.4. Example: About the differences in Macarie and Anton Pann temperaments.

The byzantine scales have 68 divisions within the octave (the Chrysantic scales used also by Macarie) but the temperaments proposed by Anton Pann were having only 22. We ask ourselves if the human ear discerns any differences when a song is played in these two temperaments.

Macarie scale has almost three times more divisions as Anton Pann scale has within the octave (68 : 22 = 3,0909). We may transform Anton Pann’s 22 divisions temperament into a 68 division temperament by increasing them 3,0909 times. To exemplify we take the first and the second echos scales and also the phthora named *muştar*. We make a table and write in the cells the new divisions for Anton Pann scales and the divisions for Macarie scales.

Comparing the successive intervals we see that the variation goes from –0,82 to +0,50 divisions. From the scale base the variation goes from –0,82 to +0,80 divisions. In both cases the variation does not exceed one Chrysantic division but the human ear can hear the differences because the ratio for one division is 1,01024547 exceeding the frequency discrimination which is 1,003.

5.6.5. Example: About the differences in Macarie, Anton Pann and equal temperament.

In this example we compare three temperaments: Macarie, Anton Pann and equal temperament (with 12 semitones) as reference. By unifying them we obtain a temperament with 2.244 divisions within the octave. Remaking the three temperaments in the new one we see that in Macarie the major tone and the minor tone are reduced and the semitone is enlarged compared to Anton Pann.

We ask ourselves if the human ear discern any differences when a song is played in these three temperaments.

To exemplify we take the first echos scale in Anton Pann, Macarie and equal temperament. We take as reference the equal temperament or Macarie to represent in a diagram the sclases steps indicating the differences between the same named steps. In the first diagram we see that the equal temperament cannot be used to play byzantine songs because its structure is too different from the others. The equal temperament rises almost all the steps in the scale, especially E and B, lowering A. The second diagram shows us that E and B are higher in Anton Pann and F and upper C are higher in Macarie. Also E – F and B – upper C are bigger in Macarie than in Anton Pann scales. Equal temperament rises E by 77 divisions (almost a quarter of minor tone) and B by 69 divisions (one third of semitone).

Anton Pann is simplifying his temperament by decreasing the semitone but increasing the major tone and the minor tone. The differences in Anton Pann divisions are greater than the same divisions in Macarie temperament.

To generalize we superpose the three diagrams and report each step to the base of each scale. For each interval the line goes to a higher point (for the higher value), a lower point (for the lower value) or remains at the same level (for an average value), having an ascending, descending or straight direction.

To verify the results we use a program from *Minerva* version 2.0, in which we may construct the 2.244 division temperament, computing the calculus for the frequencies and hearing the scales steps, in groups of 3 notes. After that the program shows the diagram for the scales variation. We can see that the differences of pitch are perceptible so we may conclude that every of the three temperaments give a specific character to the melody.

The method of reducing the temperaments to the unique temperament proves to be a good theoretical instrument.

6. COMPUTERIZED ANALYSIS

In the context of the spectacular evolution of technology, the computer proved to be an essential device in research as mathematical approach and also in science.

6.1. Computer structure – A computer is a device used to process data in a specific form, delivering the results in a simple way to the user. It is organised in two basic parts: hardware (the equipments) and software (the programs).

6.2. Using the computer in music – the personal computer may be used in the musical domain in the following ways: assisting the musician to solve theoretical problems by analysing the musical structures (music theory), making specific tasks (orchestration and counterpoint), generating complex musical structures (composition), editing scores, compiling music databases, producing the sounds by electro-mechanical means, producing the sounds by electronic synthese. A classification of computer music programs is the following one: sound recording, sound editing, sound synthese, sound restoring, score editing, databases, educational programs, utility programs, composition programs.

6.3. Computer programming – the electronic computers may solve only specific type of problems; they cannot elaborate algorithms by themselves. For using computers it must be ellaborated first the programs, the results being obtained by using algorithms. A computer language used in the Romanian education system is *Pascal* in various forms (like *Turbo Pascal*).

Musical scales may be analysed using the computer by making the numerical calculus for the frequencies followed by playing the adequate notes. It is possible to recreate the natural harmonics (considered as ascending or descending series) on any note or frequency and also it is possible to make numerical and sound comparisons between musical structures.

6.4. The "Apollo" music software – the program set *Apollo*, made by the author in 1996 (written entirely in the Turbo Pascal computer programming language), includes a lot of specialised music programs. In the main menu the operator may call a help screen by touching the F1 key and the following eight programs by using the F2 – F9 keys:

F2 Program Pann

F3 Program Macarie

The programs *Pann* şi *Macarie*, launched by pressing F2 and F3 keys, compute the frequencies and plays the sounds for all the music scales explained by Anton Pann and Macarie. For each scale are presented: a classification, the sounds and intervals and also the exact and rounded frequencies for every step in the scale. For easiness the scales were classified as following: class (temperament or intonation), sub-class (the divisions number for the temperament), group (echos or phthoras for byzantine scales), sub-group (authentic or plagal), species (diatonic, chromatic or enharmonic scale), sub-species (subordination to a specific scale), structure (derived from octave, trichord or tetrachord), name.

Each scale may be called with the F2 – F9 keys or by combining them with Shift, Ctrl or Alt keys.

F4 Theoretical programs - Minerva

The F4 key launches the "Minerva" set, with the following programs:

Minerva F2 - Program for tuning musical instruments

The computer plays the sounds demanded by the operator in the equal-tempered scale. For a good accuracy it shows the differences in fractions of Hz; the operator tunes the instrument using the beatings produced by the two sound sources: the computer and the musical instrument.

Minerva F7 - Program for computing the divisions of temperaments

Minerva F8 - Program for computing the steps of temperaments

The computer asks the number of divisions in the scale, then calculates the division. The operator gives the basic frequency and speed, then the computer shows the frequencies and plays all the divisions of the scale. The second variant allows giving the exact number of steps, the divisions being defined to the base.

Minerva F9 - Program for playing the natural harmonics

The program computes and plays the sounds of the natural harmonics (considered as ascending or descending series), for a named sound with known frequency.

F5 Solfeggio for beginners

F6 Solfeggio

The F5 and F6 keys runs a melodic solfeggio (*Euterpe* and *Orfeu*). The computer shows the score and plays the tune. In the first variant the computer shows also the notes names.

F7 Rhythmic exercise

When pressing the F7 key, the screen displays a rhythmic exercise. The computer shows the score and plays the exercise.

F8 Musical melodic dictation

The F8 key runs the program named *Hermes* for musical melodic dictating. The computer plays A^1, beats two measures and plays the tune, after that shows the tonality and the time signature. It plays three times each two measures and after that two times the same measures and the next two. When finishing this step, the computer shows the score and plays the whole tune.

F9 *Nebo* – Byzantine music

The *Nebo* program presents a byzantine score in neumatic notation, with lyrics. The tune may be played in equal-tempered scale (F2 key), Macarie with 68 divisions (F3 key – diatonic, F4 key – enharmonic, F5 key – *agem varis* enharmonic) and Anton Pann with 22 divisions (F6 key – enharmonic *agem*, F7 key – *varis* diatonic), in sticheraric (F8 key) and heirmologic (F9 key) tempo.

CONCLUSION

In general, the music theory treaties presents, more or less in detail, a part of the scales used in the music history. The subject is extremely ample, requiring a multi-disciplinary approach by defining the musical structures from the way of organization (scales, intervals, etc.), explaining the basic physical phenomena and the mathematical methods of calculus. From the didactic and practical point of view it turned out to be essential to have some methods for measuring the physical parameters using laboratory apparatus and modern computing devices.

From ancient times people were interested in music, both as art and science of sounds. Taking into consideration the growing interest of the music lovers in the ancient music, it is clear that the musical phenomena must be approached from a larger view, especially in our times when the musicological research received a substantial contribution from the mathematics, physics, electronics and computers.

This study presented the essential elements for this innovator approach, offering a solid basis for the comparative study of the musical scales and also for the complex melodic analysis of the musical works using these scales.

CONTENTS